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Preliminary modelling of acoustic detection capability for the
Drifting Arctic Monitoring System

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Abstract

The Arctic Ocean is a region of interest for Canadian defence. Here, a concept for a set of long-lived drifting acoustic monitoring arrays is proposed. The detection performance of this concept, the Drifting Arctic Monitoring System, or DAMS, is investigated via modelling. It is found that in very quiet conditions, such as that found under ice cover, detection ranges of hundreds of kilometres are possible. On the other hand, in the presence of ice cracking or other intensely noisy phenomena, DAMS is not likely to function as well. The limitations imposed by this noise could however be mitigated by a more complete picture of the nature of the ambient noise that is likely to be encountered, therefore a better understanding of the Arctic ambient noise environment is an important part in the development of the system. This could make the DAMS concept an important part of an underwater surveillance network.

Significance for defence and security

This report describes a potential acoustic surveillance system (the Drifting Arctic Monitoring System, or DAMS) for the Arctic Ocean, and gives preliminary modelling results showing the ranges for which a DAMS system could provide effective monitoring. These results indicate that in ice-covered regions, detections are possible out to hundreds of kilometres of range. The modelling also helps to predict the performance for candidate array systems and thereby serves as a design aid for the DAMS arrays.

Résumé

L'océan Arctique constitue une région dintérêt pour la défense du Canada. Dans le présent rapport, nous proposons un ensemble de réseaux dérivants de surveillance acoustique de longue durée. Nous avons étudié à l'aide de la modélisation la performance de détection de cet ensemble, soit le système dérivant de surveillance de l'Arctique (Drifting Arctic Monitoring System DAMS). Dans des conditions très silencieuses, comme celles que l'on retrouve sous la glace, nous avons déterminé que la portée de détection du DAMS peut atteindre des centaines de kilomètres. Toutefois, le DAMS n'offrira probablement pas un rendement aussi élevé en présence de bruit intense, comme le craquement de la glace. Nous croyons qu'une connaissance plus étendue de la nature du bruit ambiant susceptible d'être rencontré permettrait d'atténuer les limites imposées par le bruit. C'est pourquoi une meilleure compréhension de l'environnement sonore ambiant de l'Arctique constitue un élément important de la mise au point du système. En effet, le DAMS pourrait ainsi jouer un rôle important dans un réseau sous-marin de surveillance.

Importance pour la défense et la sécurité

Le rapport comporte la description d'un éventuel système de surveillance acoustique de l'océan Arctique, soit le système dérivant de surveillance de l'Arctique (Drifting Arctic Monitoring System DAMS), ainsi que les résultats préliminaires de la modélisation qui montrent la portée de surveillance efficace que pourrait atteindre le DAMS (dans les régions recouvertes par les glaces, la portée de détection peut atteindre des centaines de kilomètres). La modélisation facilite également la prévision du rendement de systèmes de réseaux potentiels et donc la conception de réseaux DAMS.

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1 Background

The Arctic Ocean has long been a region of interest for Canadian defence research. Issues including territorial sovereignty and resource exploitation make monitoring Arctic traffic and activities an important component of Canadian defence policy. Given the nature of acoustic propagation in the Arctic Ocean, where low frequency (sub-kHz) sound propagates for long distances near the surface, passive acoustic monitoring is potentially a very important surveillance method for both surface vessels and submarines. A recent review article by Hutt [1] provides a useful understanding of the state of acoustics in the Arctic Ocean.

In this report, we describe a potential Arctic Ocean acoustic surveillance system, which we have named the Drifting Arctic Monitoring System (DAMS). We undertake a preliminary effort at modelling the ranges for which a DAMS system could provide effective monitoring. The modelling also helps to predict the performance for candidate array systems and thereby serves as a design aid for the DAMS arrays. Note that the system description and modelling results are based on a system concept rather than an existing system.

1.1 System description

The Drifting Arctic Monitoring System (DAMS) is a concept that involves the deployment of a group of rugged, long-life, drifting buoys equipped with long, vertical, low-frequency acoustic sensing arrays to accomplish underwater surveillance in the Arctic Ocean. The drifting buoys will have on-board signal processing and communications capabilities through low data-rate satellite channels, such as IRIDIUM [2], and/or moderate bandwidth channels to aircraft or unmanned arial vehicles (UAV), which might occasionally connect to the buoy's processor for opportunistic data transfers.

The buoys will measure ambient noise and detect passive acoustic signals using advanced signal processing. Detected signals will be associated, tracked, localized, and, to a limited degree classified, by the on-board software. In general, it will not be possible to move raw data from the buoys to a remote processor and system operator; instead, the buoy processor will generate a short message using a defined protocol that can be transmitted via IRIDIUM to a remote operator station. Considerable experience with this mode of operation has been developed by participation in the NATO Next Generation Autonomous Systems Joint Research Project [3].

While it is possible to store raw acoustic data for later analysis, this will likely not be done by a DAMS buoy in normal operation. The buoy will store some data, but this is expected to be related to environmental and engineering measurements only.

Signature data will not be stored in order to avoid issues with security.

A complete Arctic Ocean surveillance system would consist of a number of DAMS buoys deployed in the Arctic Ocean to drift freely in the polar gyre, ideally using a cyclic deploy-monitor-recover-refurbish process. As we shall see, a small number of DAMS buoys, potentially only 6–12, in the Arctic Ocean at any one time would provide an impressive surveillance capability. The proposed DAMS project would carry out the basic engineering and scientific research required with a final demonstration of a small number (1 or 2) DAMS buoys to prove the concept.

Depending on the drift pattern for a DAMS buoy, the life of a buoy would be 6–18 months. The buoys will make use of battery power, augmented by solar power in the summer season. The cold temperatures and long operating duration imply that careful budgeting of energy will be required.

Figure 1 is a concept sketch showing two DAMS buoys locked in the ice with notional acoustic arrays suspended beneath. Each buoy would be initially placed in a hole created in a thick pan of ice. As we shall see from the results of this paper, DAMS buoys will generally be separated by several hundred kilometres and will not be in close proximity as depicted in the concept sketch.

The buoys will be equipped with floats to ensure the system remains buoyant in the event that it is freed from the ice and the structure of the buoy shall be sufficiently strong to withstand pressure created by moving ice. Ice buoys are relatively commonplace [4], but in general they are used for oceanographic and environmental purposes. Our suggested application, that of acoustic surveillance, is as far as we know unique at this time.

The DAMS concept sketch shows a large canister connected to the buoy by a short length of cable. This canister is the main battery case and it will be located at a depth approximately 15 m below the surface. Locating the canister on the surface, or near to the surface within the zone where ice can form, would mean that the batteries could experience very low ($-40°C$ or lower) temperatures. The battery canister will make use of the sea water to maintain the batteries at the relatively *warm* temperature of -1 to $-1.5°C$. It is important to maintain the batteries at a relatively warm temperature, because many battery technologies have reduced energy and also do not recharge well when they are cold. Depending on the chosen battery technology, the use of vacuum panels and other insulation may be required. Active heating through chemical means is also a possibility, but will be avoided if possible due to the added complexity.

The maximum buoy life-time can be obtained by deploying the buoy in the spring when the majority of operational energy can be provided by solar panels until the sun sets in the fall. During the dark months power would be drawn from the batteries.
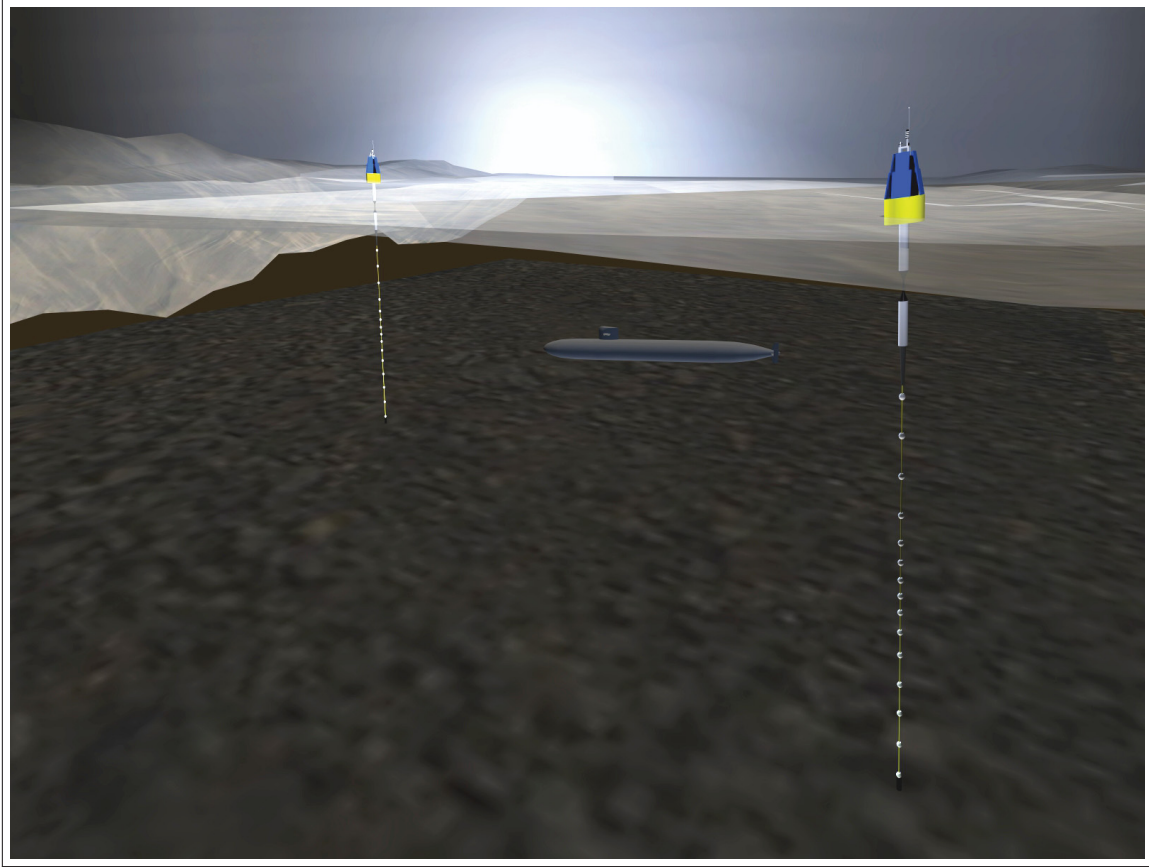
Figure 1: *Illustration of the DAMS concept. Large buoys locked in ice support vertical line arrays, which detect acoustic signals and report to remote users through a satellite communication network.*

With the return of sunlight in the spring, solar energy will be available and, if possible, excess energy will be stored in a rechargeable battery pack. It is unlikely that solar power will be sufficient to fully recharge the buoy's battery and, therefore, the buoy would normally be recovered in the late summer season resulting in the maximum endurance of approximately 18 months.

The buoy will be equipped with a long acoustic receive array (between 500 m and 1000 m long) that is designed for low frequencies. It is well known that Arctic conditions allow for long-range, near surface propagation of low frequency signals and DAMS is intended to make use of this characteristic feature. Figure 2 from Urick [5] (Adapted from Fig. 6.20, [6]) is an illustration of the advantage low-frequency signals provide. At frequencies in the tens of Hz, acoustic propagation near the surface has much less than spherical spreading loss, resulting in propagation ranges of hundreds of km.
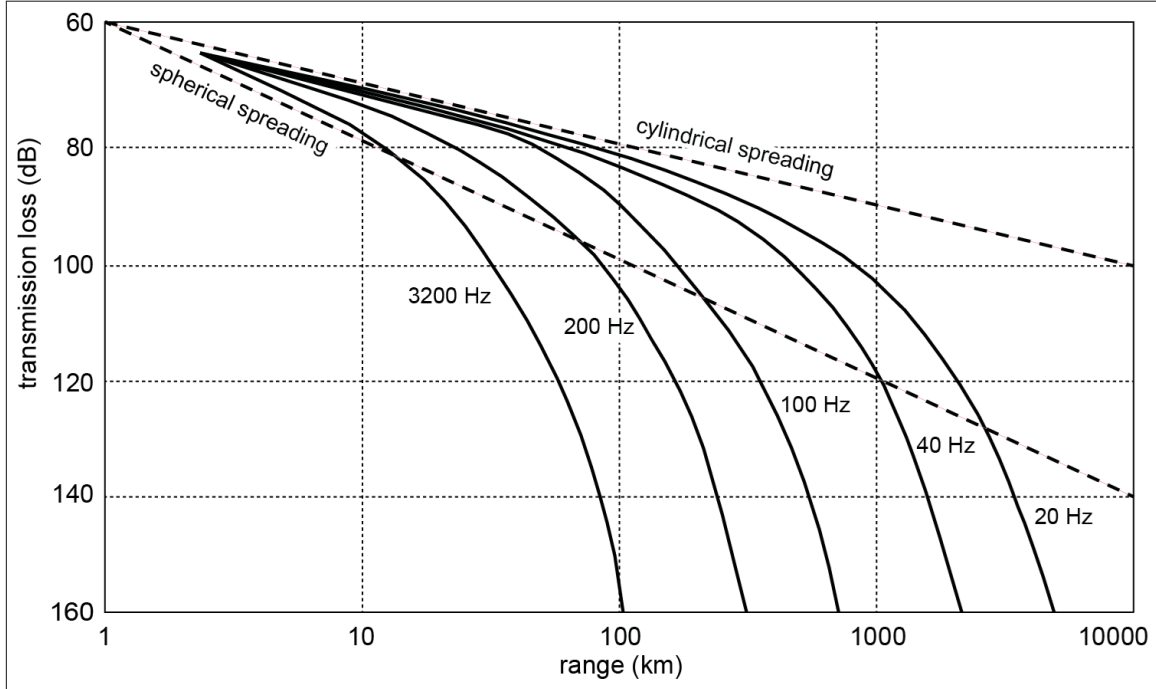
Figure 2: *Arctic acoustic transmission loss versus range for different frequencies. Low frequencies propagate best in near surface Arctic conditions. Adapted from Urick [5, adapted from Fig. 6.20].*

The array will be constructed using the Rapidly Deployable Systems Array Technology (RDSAT), which has been developed at DRDC over the last 14 years [7, 8, 9, 10, 11]. RDSAT sensor systems are intended for battery operations and produce very high quality digital data. A typical 48–64 hydrophone array and its controller generally consume less than 3 watts. A considerable fraction of this power is often expended in the array interface (Ethernet, USB) that connects the array to a computer system. The DAMS application can reduce the power requirements further by integrating the array controller with the buoy's embedded processing and moving data directly to processor memory, by using a reduced sample rate as a result of the limited frequency range. Also, because conditions are expected to be relatively static, the microprocessors at each hydrophone can be powered down once the nodes have been configured. These three array changes and design modifications should result in a significant power savings from the sensor array.

The on-board buoy processor will make use of the Linux embedded processing that DRDC has employed for several projects including the Starfish Sensor Cubes (SSC) [12, 13], Low-Complexity Access Networks (LCAN) [14], and the new Active/Passive Arctic Detection System (APADS). Currently, on-board processing algorithms for auto-detection, and beamforming exist and have been used effectively [11, 15, 16].

Recently, DRDC has begun to translate algorithms into hardware solutions using Floating Point Gate Arrays (FPGA), which are effective at carrying out complex algorithms using less power than a general computing processor. The DAMS application will make use of FPGAs for reduced energy expenditures in data processing. Target tracking software and other embedded algorithms that will be used in DAMS are currently being developed as part of DRDC's Force Anti-Submarine Warfare Project and the Autonomous Networked Surveillance Systems (ANSS) [17] work breakdown element.

The DAMS proposal provides a number of technical and research challenges, but a working prototype system is expected to be well within the current capabilities of DRDC given existing experience with battery-powered off-board sensing systems. It will be demonstrated that the DAMS proposal has considerable potential as an Arctic acoustic surveillance system.

2 Passive sonar performance calculations

A useful way to model the performance of a passive sonar system is to determine the range at which there is sufficient signal to meet or exceed a given detection threshold (DT) for a given target. There are several ways in which this can be done. One such way is to define the figure of merit (FOM) for a given frequency as:

$$\text{FOM} = \text{SL} - (\text{NL} - \text{AG}) - \text{DT}, \tag{1}$$

where NL is the noise level, SL is the source level, and AG is the array gain of the sonar system with respect to the noise. This FOM then equals the maximum one-way TL (the modelled transmission loss) that can be tolerated while providing a signal excess of 0 dB for the specified detection threshold [5]. For now, we will model the potential effectiveness of DAMS by calculating the FOM at a given frequency or set of frequencies, and comparing this to modelled transmission loss in the Arctic environment. To accomplish the modelling, we therefore need to describe the Arctic environment used to compute transmission loss. The noise component of the computation is then discussed, followed by potential source levels, and detection thresholds given the expected processing to be used by DAMS. The results of the transmission loss model and overall detection results are then discussed in Section 3.

2.1 Acoustic model and environment

Sound propagation in the Arctic differs from that in the other oceans in a number of respects. One of the most obvious of these is the prevalence of ice cover. The extent and nature of the ice cover will affect the propagation of sound in the Arctic Ocean, as well as dramatically impact the nature of the ambient noise levels.

Arctic sea ice extent and area have been diminishing rapidly over the past several decades. Figure 3 shows a plot of ice extent, *i.e.*, the area with ice concentration over 15%, in December for the years 1978 to 2013 [18]. Nevertheless, the Arctic Ocean is still ice-covered through a large part of the year, and the deep Arctic basins still have large swaths (hundreds of km across) covered by ice even at the minimum ice extent. Figure 4 shows the areas in the Arctic that have been typically covered by ice near the sea ice minimum and maximum, over the period 1981-2010.

Water depths in the basins of the Arctic Ocean vary from about 2800–4000 m deep. Arctic oceanography consists of three main water masses [19], the Arctic, Atlantic, and Arctic Deep water masses, whose density structure is determined largely by salinity. As described by Pickard and Emery [20], the surface Arctic water mass (extending down to about 200 m depth) circulates clockwise with speeds of 1 to 4 cm/s. The surface water layer (top 25 to 50 m) has a temperature near the freezing point of sea water, about –1.5° C, and salinity that varies geographically from 28 PSU
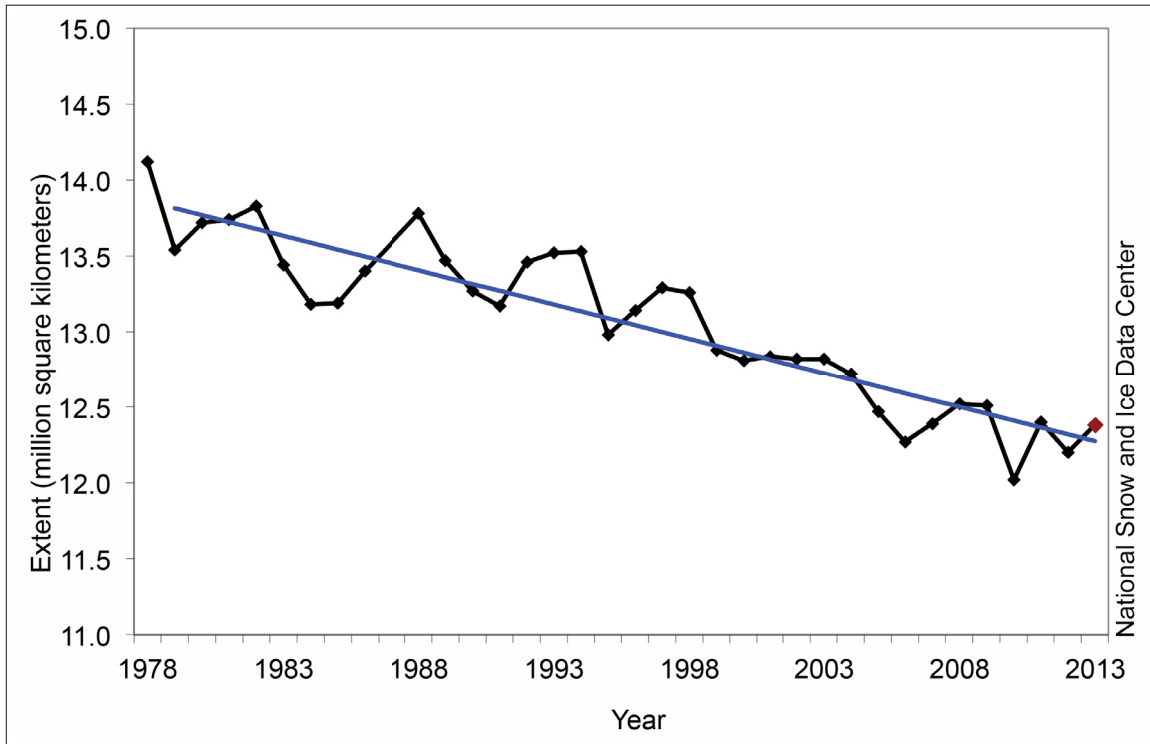
Figure 3: *Monthly sea ice extent for the month of December, 1978-2013. The blue line indicates a trend of 3.5% loss per year [18].*

to 33.5 PSU. Seasonal variations in temperature and salinity are usually quite small (smaller than regional variations). Below the surface layer is another layer with a halocline to about 100 m, which is near-isothermal in the Eurasian Basin, but has a temperature maximum at 75 m to 100 m in the Canada Basin, due to the incursion of warmer, saltier Bering Sea water through the Bering Strait. Deeper still is a mixing layer intermediate between the subsurface Arctic mass and the Atlantic water mass below. This water, which extends from about 200 to 900 m depth, is warmer than the water above and below. The third water mass, the Arctic Deep, has a very stable salinity of about 34.9 to 34.99 PSU horizontally and vertically, with temperature minima of about –0.8° C at 2500 m depth in the Eurasian Basin and 0.4° C in the Canada Basin at 2000 m.

For the purposes of modelling acoustic propagation, we assume a typical winter sound speed profile for the Canada Basin in the Arctic Ocean (see Figure 5), and a constant bottom depth of 3800 m. Total sedimentary cover thicknesses in the Arctic have been compiled in [21], and range from areas of little sediment (less than 2 km) near the pole, to regions where thickness is over 12 km. Sediment thicknesses in the Canada Basin are about 6–10 km, where the surficial layers seem to be primarily silty clays
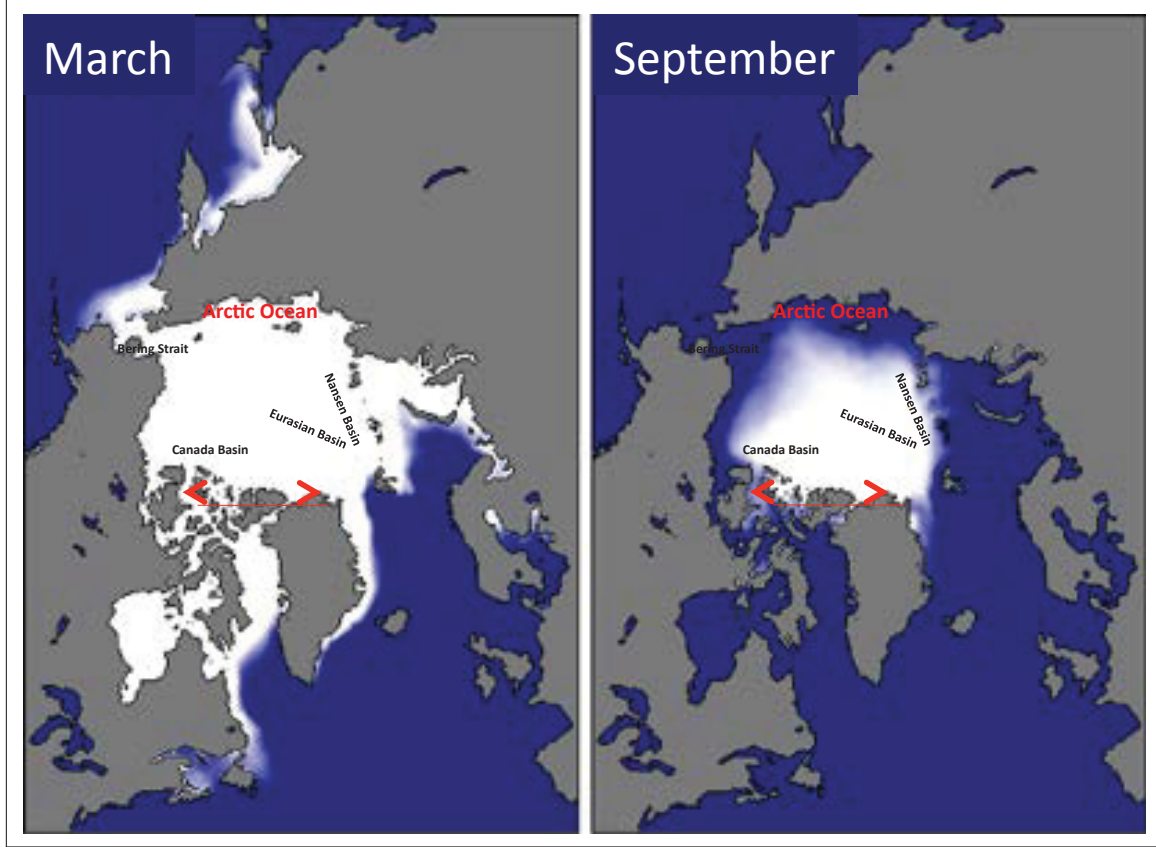
Figure 4: *Average Arctic ice cover for March and September over the period 1981-2010 [18]. Red arrow is 2000 km in length.*

[22, 23]. For modelling purposes, we assume a sedimentary rock or limestone half-space underlying mostly silty sediment, with the surficial layer being about 100 m thick. The layers are modelled using the geoacoustic parameters given in Table 1, which is also consistent with measurements acquired in the Nansen Basin [24]. The exact nature of the bottom sediment is not crucial, due to the upward refracting profile and large water depth.

Acoustic propagation models differ in their ability to handle propagation under ice, and in fact, modelling the effects of an ice surface on propagation is an active area of research [25, 26, 27, 28, 29]. For the purposes of this study, we will treat the ice as a rough elastic layer with a thickness of 4 m The density of sea ice is 0.92 g/cm^3, and we will use for the geoacoustic parameters $c_p = 3500$ m/s, $c_s = 1500$ m/s, $\alpha_p = 0.5$ dB/λ, $\alpha_s = 1.0$ dB/λ. The roughness along the ice-water interface was defined as Gaussian with an RMS roughness of 1.9 m and a correlation length of 40 m. These parameters are similar to those used in previous studies [30].
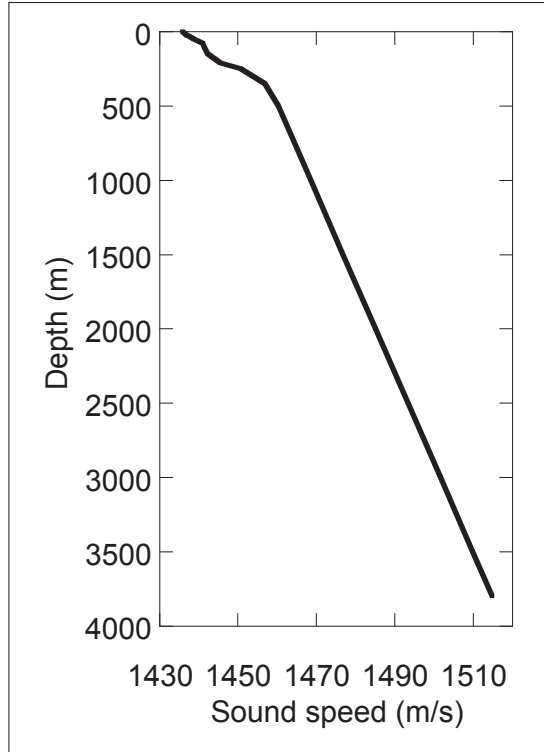
Figure 5: *Typical winter sound speed profile for the Canada Basin.*

Table 1: *Geoacoustic parameters for propagation modelling.*

Parameter	Upper layer	Basement
Thickness	100 m	half-space
Density ρ	1.7 g/cm^3	2.4 g/cm^3
Compressional sound speed c_p	1.05c_w	3 km/s
Shear speed c_s	0.5 km/s	1.5 km/s
Compressional attenuation α_p	1 db/λ	0.1 dB/λ
Shear attenuation α_s	1.5 db/λ	0.2 dB/λ

2.2   Noise background

The noise background is an important term in Eq. 1. The two components of this noise are ambient noise, and self-noise. Set against this is the array gain, i.e., how well the array reduces the effects of noise on an incoming signal.
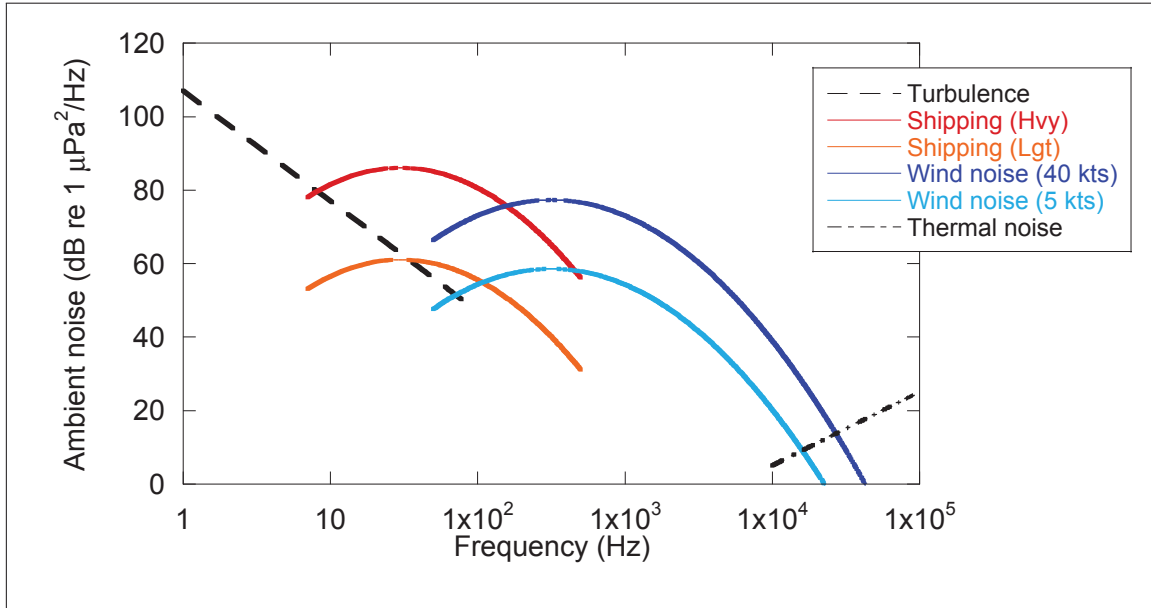
Figure 6: *Wenz noise curves for varying wind speeds and shipping levels.*

2.2.1   Ambient noise levels

Ambient noise level, as applied in this analysis, is the intensity of the ambient background relative to the intensity of a plane wave with 1 μPa RMS pressure, as measured using an omnidirectional hydrophone [5]. The directionality of both the noise and the receiver will impact the effect that this ambient noise will have on detection. The nature of the noise depends on the frequencies of interest and on the conditions causing the noise.

Urick [31] provides a summary of much of the early work done in studying ambient noise. In typical mid-latitude open ocean, ocean turbulence and seismic disturbances, or microseismicity, can be a heavy contributor to ambient noise, dominating the noise background at frequencies lower than a few tens of Hz. Above this frequency regime, in the range from about 50 Hz to about 500 Hz, shipping tends to be the dominant noise source. Over frequencies from several hundred Hz to about 25 kHz, ambient noise is generally dominated by wind-related processes. These processes include wind turbulence, surface motion, wave interactions, and spray and cavitation. At very high frequencies, molecular thermal noise rises with frequency at a rate of 6 dB per octave, eventually dominating the noise background. Figure 6 shows the curves that describe the power spectral level of ambient noise according to the Wenz model [32], for wind speeds of 5 and 40 knots, and light and heavy shipping levels. In many of these frequency bands, high ambient noise backgrounds due to biological activity can also present themselves.
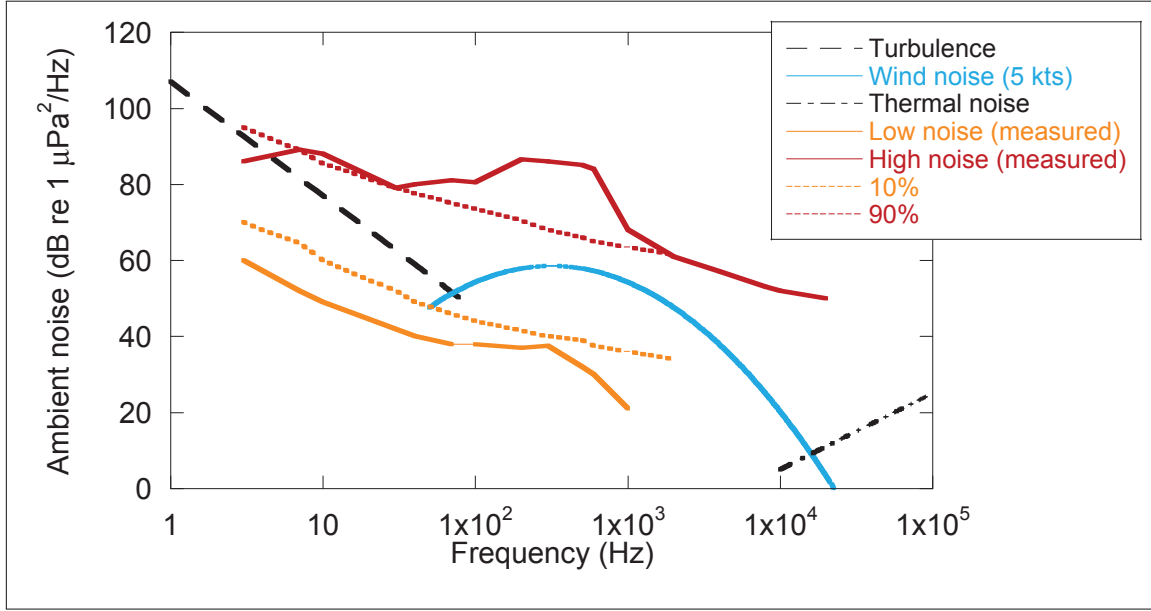
Figure 7: *Ambient noise curves for Arctic areas based on [31, 5].*

In the Arctic, the noise background can be quite different. Broadband noise from biological sources is usually less, particularly in conditions of full ice cover. Similarly, ambient noise from distant shipping is also often reduced. Wind noise is still found, but observations have shown that it is stronger for partial ice cover, while for full ice cover the noise levels are independent of wind speed [33, 31]. Other noise sources include tensile ice cracking, which tends to produce strong impulsive sources as air temperatures drop [34, 35]; ice movement, including rubbing and colliding of floes, and ice fissuring at mid-frequencies [36], as well as pressure ridging at low and medium frequencies [37]. In areas of partial ice, or near the marginal ice zone, waves crashing on ice floes are also a source of ambient noise. A compilation of ambient noise power spectra measured in the Arctic can be found in [31]. Based on that data and estimated prevalence levels for ambient noise in the Arctic from [5], Figure 7 shows potential ambient noise curves for Arctic areas. Noise spectral levels can differ greatly depending on the prevailing conditions; for example, the low noise curve, based on measurements in an area of old polar ice in April 1961 with no ice cracking [36], is 40–50 dB lower than the high noise curve (shore-fast thick ice measured in February 1963 with frequent cracking [36]) from 10 Hz to 1 kHz.

2.2.2   Array gain

It is anticipated that the DAMS array will have multiple apertures, with a length of between 500 m and 1000 m, *i.e.*, up to 20-λ in length for a 30 Hz signal. The number of sub-array elements is not yet determined, but somewhere between 24–64 elements

is likely. In addition, at least some elements of the array would have an azimuthal directivity in order to allow determination of the signal bearing. The combined vertical and horizontal directivity can easily be expected to provide a directivity index, DI, of up to 16 dB. In the idealized case, directivity index equals the array gain relative to ambient noise. In reality, the array gain will fluctuate depending on the coherence of the acoustic signal; for example, the presence of internal waves typically reduces signal coherence and array gain. In the case of under-ice propagation, for low frequencies acoustic signals show near-ideal coherence temporally, with tonal signals up to 40 Hz having stable relative phases over long ranges [38]. Basin-scale experiments have also shown long distance spatial and temporal coherence [39, 40].

Typically, ambient noise is considered to have a Gaussian amplitude distribution, and to be approximately isotropic. The noise found in the Arctic due to ice cover is frequently non-Gaussian [41, 36, 42], and may have significant directionality associated with it [43]. Without some further knowledge of the typical conditions that will be encountered by DAMS, it is difficult to determine how best to process data from an array to minimize noise. It is possible that a higher gain might be realized against the directional non-Gaussian noise (possibly generated by local sources near the surface) when the target is a distant submerged one, as compared to the usual assumptions of Gaussian, isotropic noise. For example, in azimuthally isotropic noise that is confined to a horizontal plane, the array gain at broadside can be 2 dB greater than the DI [44]. For the modelling in this report, an array gain of 16 dB is used.

2.2.3 Array self-noise

In very low ambient noise conditions in the Arctic, array self-noise could potentially limit the performance of DAMS. Electronic system noise can generally be made lower than the ambient noise level; however, this low system noise comes at the expense of increased power dissipation in the hydrophone preamplifiers. Due to the long endurance required of the DAMS with a battery power source all current consumption must be minimized. Fortunately, DRDC has considerable experience with a suitable array technology that combines low-power and low-system noise [45].

It is also possible that hydrodynamic noise could affect array performance. However, typical currents in arctic near-surface waters are quite slow, averaging 1–4 cm/s [20]. Based on experimental data [46], the flow noise on a hydrophone of 10 cm diameter from a 4 cm/s current could exceed the lower limit of ambient noise shown in Figure 7 for frequencies below 30 Hz, with noise levels of 45 dB re $1\mu\mathrm{Pa}^2/\mathrm{Hz}$ at 30 Hz and 65 dB re $1\mu\mathrm{Pa}^2/\mathrm{Hz}$ at 15 Hz. Depending on the relative drift rate of DAMS, some or all of the hydrophones could experience this type of flow noise, so the design choices for DAMS will affect levels of hydrodynamic noise experienced by the array.

2.3   Source levels

The assumed threat source level (SL in Eq. 1) spectrum is based on the values given by Urick [5, p.318], based on WWII-era electric submarines operating at the surface at a speed of 4 kts (originally found in [47]). A set of power spectral levels for various frequencies, along with a broadband level for the 400 Hz to 800 Hz band, is shown in Table 2.

Table 2: *Threat source level spectrum.*

Frequency (Hz)	Source level (dB re $1\mu\text{Pa}^2/\text{Hz}$)
15	141
50	133
150	126
300	122
600	117
Broadband	146 $(120 + 10\log_{10} 400)$

2.4   Detection threshold

The computation of the detection threshold (DT) for each frequency depends on the nature of the acoustic signals, the noise background, usually assumed to be Gaussian, and the type of processing. Tonal signals received from a distant source on an array behave like narrowband Gaussian noise [48]. If a received signal is split into processed segments, the assumption that these segments are uncorrelated, *i.e.*, that the segments are processed incoherently, is a Swerling II signal model for the signal amplitude fluctuations. Walker [49] describes how the detection performance of FFT processing of such a signal can be evaluated, based on the processor parameters selected, giving the equation:

$$\text{DT} = \text{G}_{\text{M}} + 10\log_{10}\text{B} + \text{L}_{\text{w}} + \text{L}_{\text{r}} - \text{G}_{\text{z}} - \text{G}_{\text{o}} + \text{L}_{\text{n}}, \qquad (2)$$

where G_{M} is the basic detection threshold (based on the desired probabilities of false alarm and detection) for a given signal type (in this case Swerling II) with a given time-bandwidth product (here, the record length or integration time multiplied by the FFT bin width); B is the FFT bin width; L_{w} and L_{r} are the data windowing and ripple losses; G_{z} and G_{o} are the gains due to zero-padding and overlapping of the FFT segments; and L_{n} is the loss due to data normalization, *i.e.*, adjacent bins used to estimate noise power.

For the purposes of this analysis, we assume an integration time of 5 minutes, using FFT lengths of 8 seconds for the 15 Hz and 50 Hz signals and 4 seconds for the

150 Hz and higher frequency signals, giving a time-bandwidth product of 37.5 and 75 respectively. A 50% overlapped Hann window will be assumed, along with the use of 20 normalizer bins for noise power estimate. The resulting detection thresholds for the narrowband signals, based on varying probability of detection (P_d) and probability of false alarm (P_{fa}) are given in Table 3.

Table 3: *Detection thresholds (DT) in dB for given P_d and P_{fa}.*

Frequency (Hz)	DT (dB) for $P_d = 0.9; P_{fa} = 10^{-4}$	DT (dB) for $P_d = 0.99; P_{fa} = 10^{-4}$	DT (dB) for $P_d = 0.9; P_{fa} = 10^{-6}$
15	-8.2	-6.7	-6.8
50	-8.2	-6.7	-6.8
150	-7.3	-6.0	-5.9
300	-7.3	-6.0	-5.9
600	-7.3	-6.0	-5.9
Broadband	-12.0	-11.1	-11.2

In the case of broadband signal detection, following the analysis of Ainslie [44, p.597], for a fluctuating signal in Gaussian noise where the time-bandwidth product is high enough, the detection threshold can be approximated by:

$$DT(P_{fa}) \cong 10 \log_{10}(\mathrm{erfc}^{-1}(2P_{fa})) - 10 \log_{10} \sqrt{2BT}, \tag{3}$$

for a P_d of 0.5, where BT is the time-bandwidth over which the incoherent processing is averaged. Given the 400 Hz bandwidth assumed above, and a 16 second integration time, this results in the detection thresholds shown in Table 3.

The detection threshold can also be affected by processing multiple potential detections, within or across frequencies. Gains can potentially be realized by using either a binary integrator (*i.e.*, 'M of N' approach) [50, 51] or a single or multiple 'OR' operation for detections [44]. These are not considered here.

3 Results

3.1 Figure of merit

Given the results of the previous section, the FOM defined in Eq. 1 may now be computed. The detection thresholds used are those tabulated in Table 3, the source levels are from Table 2, and the noise level is given by the bounds of the minimum and maximum ambient noise minus the array directivity index (except for the low noise state, where for 15 Hz and 50 Hz the assumed flow noise experienced by the array is used). The results of calculating the FOM are found in Table 4.

Table 4: *Figures of Merit (FOM) for narrowband and broadband detections for varying P_d and P_{fa}, for low and high noise conditions.*

Frequency (Hz)	FOM (dB) (low,high) $P_d = 0.9; P_{fa} = 10^{-4}$	FOM (dB) (low,high) $P_d = 0.99; P_{fa} = 10^{-4}$	FOM (dB) (low,high) $P_d = 0.9; P_{fa} = 10^{-6}$
15	85, 81	83, 80	84, 80
50	114, 77	112, 75	112, 75
150	112, 668	111, 65	110, 64
300	108, 59	107, 57	106, 58
600	110, 56	109, 55	109, 55
Broadband	104, 66	103, 65	103, 65

The differences in the FOM in low noise conditions as compared to high noise conditions are very large (up to 50 dB), particularly for the highest frequency narrowband case. The best FOM is obtained for the 50 Hz narrowband signal in low noise. In high noise, the 15 Hz signal performs best, as at this point the ambient noise is nearer the flow noise floor. There is almost no difference between the cases where $P_d = 0.9$ and $P_{fa} = 10^{-6}$ are used, as compared to $P_d = 0.99$ and $P_{fa} = 10^{-4}$. In practice, given the large number of frequency bins that will potentially be processed, it is probably desirable to set the false alarm rate even lower than 10^{-6}.

3.2 Transmission loss

The FOMs computed in Section 3.1 can now be compared to modelled one-way transmission loss, giving a detection range for the specified P_d and P_{fa}. The OASES wavenumber integration model [52] is used with the environmental parameters specified in Section 2.1, for the frequencies of interest, with assumed target depths of 50 m and 500 m. Transmission loss for the broadband case is assumed to be approximately
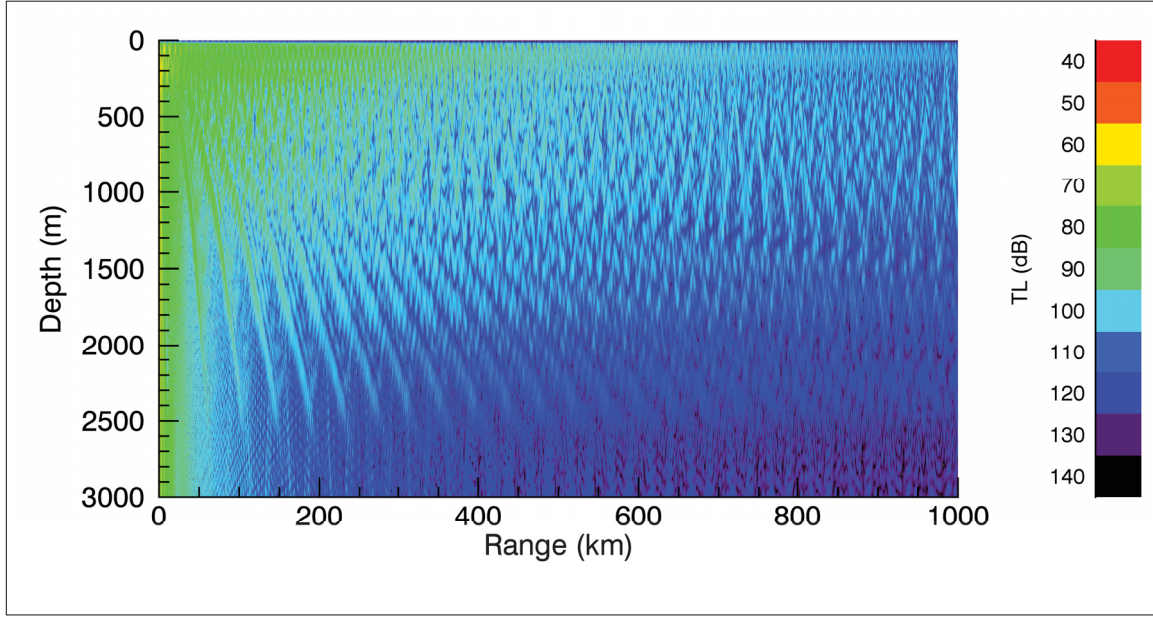
**Figure 8:** *Full field transmission loss in Arctic environment at 50 Hz for a source at 50 m depth.*

equal to that for the centre frequency, *i.e.*, 600 Hz. The depth-averaged transmission loss is calculated for receivers from 10 m to 500 m deep, corresponding to the anticipated depths of the DAMS array elements.

Figure 8 shows an example of the transmission loss modelled for a frequency of 50 Hz for a 50 m deep source. The transmission loss plotted in Figure 8 shows that comparatively low losses are expected over the part of the water column occupied by the DAMS array, with most of the acoustic energy propagating through the surface duct. Given the relatively low losses for depths through the first few hundred metres of the water column and the lack of a strong interference pattern in the TL plot, it is likely that beamforming can be done using an array of the length envisaged.

3.3   Detection results

The transmission loss can now be plotted against the FOMs from Table 4 to determine detection ranges for DAMS against the target. Figure 9 shows an example for the TL for a 50 Hz signal with the FOM for the low and high noise 50 Hz narrowband detections, using $P_d = 0.9$ and $P_{fa} = 10^{-6}$. Although the fluctuations in TL indicate that detections could be expected intermittently at longer ranges, for the high noise case, detection ranges are limited to about 28 km for the shallow target, and 8 km for the deep target. For the low noise case, detection ranges are much higher. In both
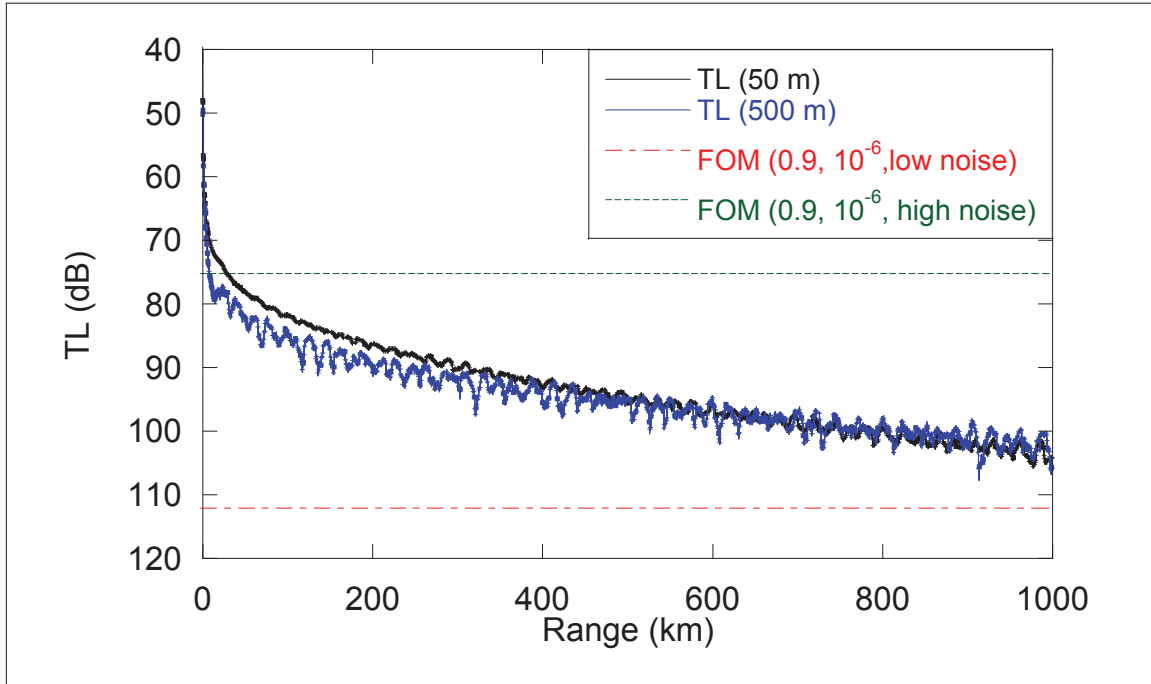
Figure 9: *Transmission loss (TL) and Figure of Merit (FOM) vs. range for deep (500 m) and shallow (50 m) targets at 50 Hz.*

the deep and shallow target cases, detections are consistent to over 1000 km. A 0 dB signal excess would still be possible at ranges out to over 900 km for ambient noise conditions 10 dB higher (or alternatively source levels 10 dB lower).

Detection ranges (DR) for each of the conditions considered are tabulated in Tables 5 and 6, for shallow and deep targets, respectively. The range given is the mean range beyond which signal excess drops below 0 dB—signal excess might still be positive in certain range bands beyond these ranges, particularly for the deeper target, where greater fluctuations in coherent transmission loss are seen. Detection ranges of over 1000 km are given as 1000 km.

Except for the lowest frequencies where flow noise likely limits the performance of the DAMS array, the lower frequencies give the best detection performance in the low ambient noise case, with a fairly rapid decrease in anticipated detection range as frequencies increase to the hundreds of Hz. In the high noise case, detection ranges are quite poor except at the lowest frequencies, where ambient noise does not limit performance. However, it is worth noting that the high noise case typically corresponds to ice conditions found nearer to shore, while the ambient noise in the ice-covered deep Arctic is typically expected to be closer to the low noise case. In most cases, the detection ranges for the deep target and the shallow target are comparable.

Table 5: *Detection ranges for narrowband and broadband detections for varying P_d and P_{fa}, for low and high noise conditions, for a 50 m deep target.*

Frequency (Hz)	DR (km) (low, high) $P_d = 0.9; P_{fa} = 10^{-4}$	DR (km) (low, high) $P_d = 0.99; P_{fa} = 10^{-4}$	DR (km) (low, high) $P_d = 0.9; P_{fa} = 10^{-6}$
15	58, 33	50, 21	50, 30
50	1000, 37	1000, 27	1000, 28
150	210, 2.7	180, 2.3	180, 2.3
300	84, 1.0	82, 0.8	82, 0.9
600	100, 0.7	100, 0.6	96, 0.6
Broadband	54, 2.3	53, 2.2	53, 2.2

Table 6: *Detection ranges for narrowband and broadband detections for varying P_d and P_{fa}, for low and high noise conditions, for a 500 m deep target.*

Frequency (Hz)	DR (km) (low, high) $P_d = 0.9; P_{fa} = 10^{-4}$	DR (km) (low, high) $P_d = 0.99; P_{fa} = 10^{-4}$	DR (km) (low, high) $P_d = 0.9; P_{fa} = 10^{-6}$
15	58, 32	36, 11	36, 11
50	1000, 9.9	1000, 7.8	1000, 8.0
150	230, 2.3	220, 2.0	220, 2.0
300	104, 1.0	104, 0.8	104, 0.8
600	105, 0.6	104, 0.5	104, 0.5
Broadband	71, 2.2	71, 1.9	71, 1.9

Figure 3.3 graphically indicates the coverage that could reasonably be achieved with the DAMS buoys. The light gray region, or good acoustic condition range, is ∼600-km, and indicates the detection ranges for a 15 Hz signal in noise conditions 12 dB higher than the low noise conditions shown in Tables 5 and 6 (corresponding to the 10th percentile noise curve from Fig. 6). The darker centre represents a more conservative 200-km detection range that would result for a 20–25 dB increase in the noise level above the low noise threshold.
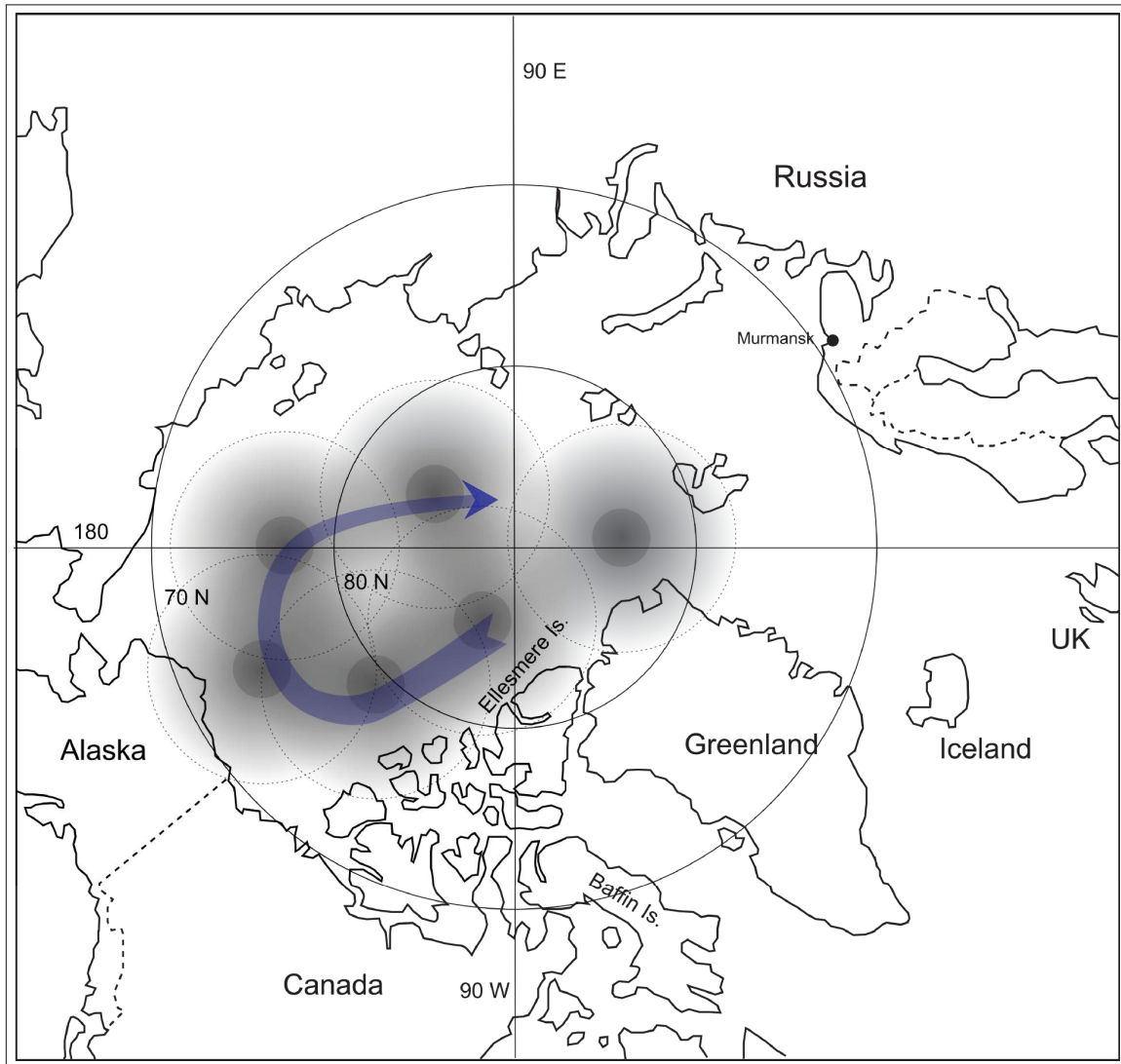
Figure 10: *Polar map shows the potential for areal coverage by six DAMS buoys freely drifting in the Arctic Gyre. The dark centre represents a conservative 200-km detection range, while the gradient-filled larger circles represent a 600-km detection range in good acoustic conditions.*

4   Conclusions

The DAMS concept, for a set of long-lived drifting arrays with on-board processing, relies on the nature of acoustic propagation in the Arctic. Given the very quiet conditions that can be found under ice cover, detection ranges of hundreds of kilometres are feasible. On the other hand, in the presence of ice cracking or other intensely noisy phenomena, DAMS is not likely to function as well. The problem of ambient noise limiting the detection range for DAMS can be mitigated by a better understanding of the nature of the ambient noise in the Arctic. Additional research into both Arctic environmental conditions and signal processing for under-ice arrays can lead to better processing and improved signal to noise ratios. These improvements could make the DAMS concept, already a promising idea for part of an underwater Arctic surveillance network, even more valuable.

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The Arctic Ocean is a region of interest for Canadian defence. Here, a concept for a set of long-lived drifting acoustic monitoring arrays is proposed. The detection performance of this concept, the Drifting Arctic Monitoring System, or DAMS, is investigated via modelling. It is found that in very quiet conditions, such as that found under ice cover, detection ranges of hundreds of kilometres are possible. On the other hand, in the presence of ice cracking or other intensely noisy phenomena, DAMS is not likely to function as well. The limitations imposed by this noise could however be mitigated by a more complete picture of the nature of the ambient noise that is likely to be encountered, therefore a better understanding of the Arctic ambient noise environment is an important part in the development of the system. This could make the DAMS concept an important part of an underwater surveillance network.

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